Nendica Contribution

Technological Enhancement of Networking for Flexible Factory IoT –Gap Analysis–

May 14. 2018

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Technological Enhancement of Networking for Flexible Factory IoT

Concept

The future flexible factory communication system comprises integrated wired/wireless-combined networking which needs to accommodate various system applications with different communication requirements for end-to-end QoS. These requirements are satisfied for end-to-end communications by reinforcing priority control and coordinating with those system applications to adapt to rapid change in links and paths quality.

Gaps in existing IEEE 802 technologies

Coexisting of wide variety of factory applications with different requirements

According to Figure 11 and Table 2~14 in Section "Wireless Applications and Communication Requirements" [1], examples of QoS tolerances in factory applications are summarized in Table 15. Table 15 shows that tolerance of latency is classified into small, medium or large, tolerance of bandwidth is classified into wide, medium or narrow, and tolerance of packet loss is classified into lossless or not. It means that factory applications may need large number of QoS class requirements for communications, which is not covered by 8 classes defined in IEEE802.1D standard. To deal with large number of QoS class requirements, defining usage of tag fields may be needed for precise and fine QoS control in L2.

Table 15 Examples of QoS Tolerances in Factory Applications

Category of Wireless Applications	QoS Tolerances							
	Latency (msec)			Bandwidth (kbps)			Packet Loss	
	<100	100~ 1000	>1000	>1000	100~ 1000	<100	Loss less	Non-Loss less
Equipment Control	✓	✓				✓	✓	
Quality Supervision	✓	✓	✓	✓	✓	✓	✓	
Factory Resource Management		✓	✓	✓	✓	✓	✓	✓
Display		✓	✓	✓	✓	✓	✓	✓
Human Safety	✓		✓	✓	✓	✓	✓	✓
Others		✓	✓	✓			✓	✓

QoS management for factories

QoS management of streams across their paths is important in the automation of factories. There are several functions and protocols within existing IEEE802 standards that maybe used for the provision of QoS and priority control over bridged network. Example of such functions are given as follows.

802.1Qat Stream Reservation Protocol (SRP):

Stream Reservation Protocol (SRP) is an amendment to the IEEE 802.1Q standard (standardized separately as 802.1Qat) to provide end-to-end management of resource reservations for data streams requiring guaranteed Quality of Service (QoS) in bridged Local Area Networks (LANs).

The protocol allows end stations to register their willingness to "Talk" or "Listen" to specific streams, and it propagates that information through the network to reserve resources for the streams. Network bridges between the end stations maintain bandwidth reservation records when a Talker and one or more Listeners register their intentions for the same stream over a network path with sufficient bandwidth and other resources.

The network signaling for SRP to establish stream reservation is defined as the Multiple Stream Registration Protocol (MSRP), which is also standardized in 802.1Qat.

Enhancements to the configuration of time-sensitive Streams are provided by P802.1Qcc /D2.1, amendment to IEEE Std 802.1Q-2018. The enhancements address Time-Sensitive Networking (TSN) application requirements beyond audio/video (AV) traffic. It also specifies managed objects for configuration of Bridges by a Centralized Network Configuration (CNC) component.

802.11aa MAC enhancement for robust AV streaming:

802.11aa specifies a set of enhancements to the 802.11 MAC functions which enables the transportation of AV streams with robustness and reliability over wireless shared medium.

From the bandwidth reservation standpoint an IEEE 802.11 BSS network is modeled as a Bridge. An IEEE 802.11 BSS provides a single entity called the Designated MSRP Node (DMN) to manage the BSS bandwidth resources for the MSRP streams. The DMN maps the MSRP commands into IEEE 802.11 MLME/SME QoS services, and maps the SRP TSpec to 802.11 TSPEC parameters as well.

Interworking between 802.1Qat and 802.11aa enables integration of 802.11 TSPEC ADDTS request/response protocols with SRP to facilitate end-to-end stream reservations when one or more IEEE 802.11 links are part of a path from Talker to Listener.

Issues:

To announce the statistics of the stream to be provided, Talker should make a declaration of ‘Talker Advertise’ which would be propagated by MSRP throughout the network. In the parameter data carried by the declaration advertisement, a component of ‘Accumulated Latency’ is used to estimate the worst-case latency that a stream could encounter from Talker to Listener. Talker initializes the value and each bridge along the path will add the maximum expected delay before arrival at the next peer.

Radio propagation is not good in factories due to multipath and shadowing environment in metal objects presence and closed space, so latency fluctuation over radio link is large. If such event occurs e.g. on Bridge C in Figure 18, that would increase the latency beyond the original guarantee (e.g. Accumulated Latency), MSRP will change the ‘Talker Advertise’ to a ‘Talker Failed’ causing the end-to-end reservation to be failed as shown in Figure 18. For this reason in a factory environment, ‘failure’ frequently occurs so that streaming cannot be provided in some cases.

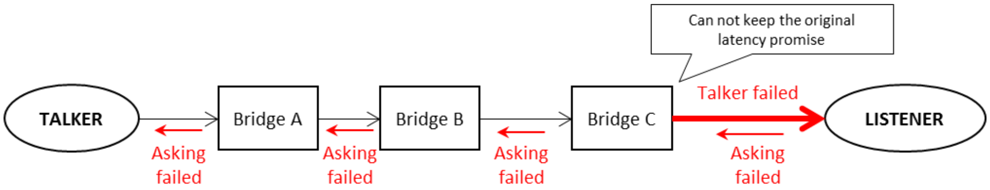

Figure 18 Radio fluctuation causes reservation failed

Besides the example given above, there will be similar problems considering bandwidth reservation in the factory wireless environment. The matter is that, the bridge currently determines the registration and allocation of the resources from its own perspective. Along the declaration propagated throughout the network, decision is made on individual bridge's 'worst' estimation on the performance of current hop. In some cases, it could be much worse than the actual performance. In other cases, it could be breached very often.

Coordinated control among the bridges is necessary to help the situation by addressing the unstable bandwidth / latency issues. The controller could manage the resources from an end-to-end viewpoint during the lifetime of the stream. The performance fluctuation can be more tolerated as long as the end-to-end bandwidth can be guaranteed. With such flexibility, robustness of the end-to-end stream reservations, as well as the network efficiency, will be improved.

Other TSN protocols:

TSN provides a protocol suite to enable deterministic networking end-to-end. Future industrial wireless products should be able to take advantage of this infrastructure. It requires higher layer services to be better interworking with lower layer management entities.

As the fundamental architectural issues cleaned up by 802.1Qbz and 802.11ak, and given the fact that great potential will be introduced to wireless technologies by e.g. 802.11ax, 802.11ba, it is now possible to extend more advanced protocols such as Flow-based Priority Control (FPC) and Enhanced Transmission Selection (ETS) to the wireless shared medium.

Adaptation to rapid changes in wireless environments

Modern manufacturing process requires fast feedback to get immediate response after each action by worker in management and operation to increase high productivity and high quality of products, simultaneously, where human and machines tightly collaborate in high-mix and low-volume production. Permissible delay in feedback messages for most wireless applications in this sense is ranging from 20 msec to 10 sec as shown in Figure 11. The lower boundary may be determined by human reaction time [2]. For example in an application in which an online inspection, an action by worker is checked by a system whether it is good or not. He/she shall receive go/no-go signal from the system indicating to whether to proceed to the next action or not. In the network accommodating factory applications such as quality supervision, factory resource management, display, and some of equipment control and safety, permissible latencies within 100 msec or less for communications between a terminal and a management system of the factory application is considered reasonable.

In a typical factory structure (or layout), there are many metallic objects that are moving in a closed space, resulting in unforeseeable fluctuation in received radio signal indication (RSSI) due to rapid change in propagation condition. An example of measurement in a metal casting site showed RSSI changed by more than 20dB within a short time ranging from ten's millisecond to hundred's millisecond as disused earlier in Figure 4. The bandwidth might decrease by one-tenth in a case during RSSI dropped. Another example of measurement in a large machine assembly site indicted burst-loss occurred for the duration of several hundred msec as shown in Figure 16.

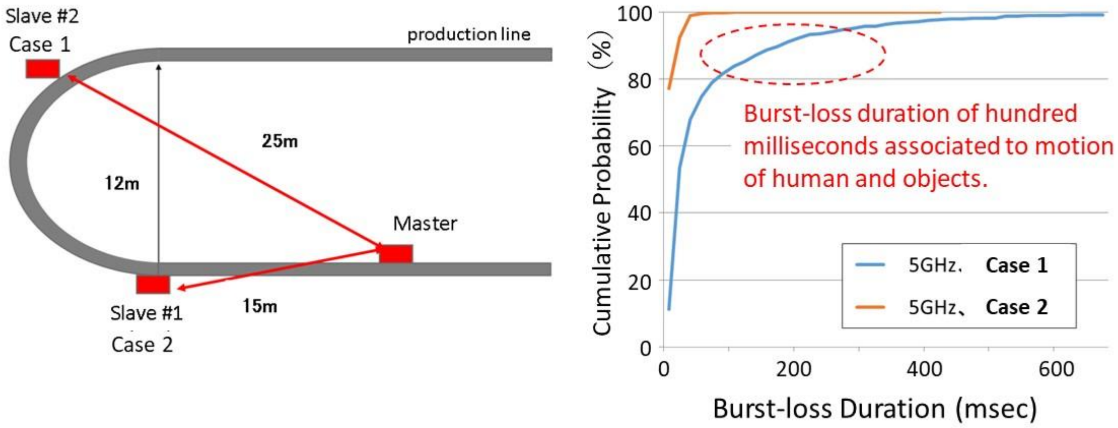

Figure 16 Burst-loss measurement in a large machine assembly site [2]

In order to ensure transfer of information between terminals in a dynamically changing wireless environment within the allowed latency as required by factory applications, a fast and efficient queueing control and forwarding mechanism to multiple links is needed while maintaining required QoS for the application. For this purpose, we consider the applicability of the PFC (Priority-base Flow Control) protocol specified in the Std. 802.1Q-2014, as shown in Figure 17.

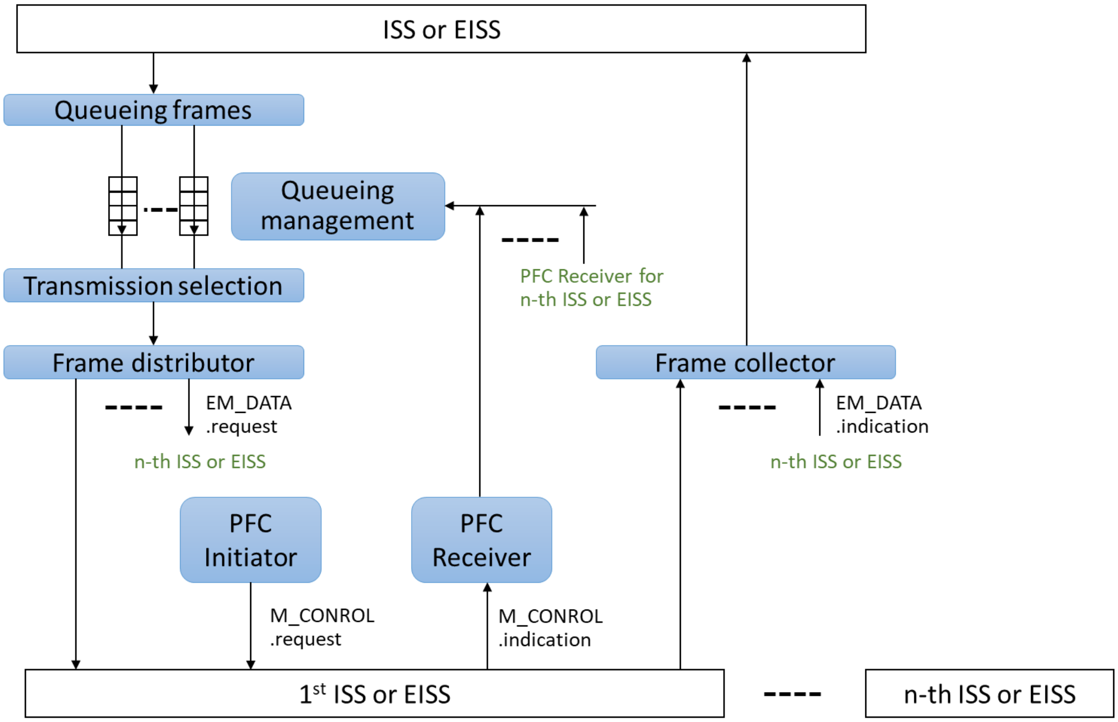

Figure 17 PFC aware system queue functions with Link Aggregation (Rewritten Figure 36-4 in Std. 802.1Q-2014)

It should be noted that the application of PFC has been so far used in data center environment[1]. However, when used in a factory environment such as the one described above, the performance and efficiency of the PFC protocols can be degraded significantly due to reduced available bandwidth between terminals. A real time video streaming is a good example illustrating when the performance of the PFC function can be improved when operating in varying radio propagation conditions. Traffic for the video stream is allocated high priority in normal operation condition (i.e. traffic type for video has higher priority than traffic for critical applications according to Table I-2 in the Std.802.1Q-2014 [4]). With varying RSSI, the available bandwidth between terminals is reduced. In real time video streaming application, video quality can be adapted to available link bandwidth (along the end to end path) at the codec source. However, until this video adaptation is complete, while the bandwidth of the link is low and the video quality is degraded below its usable level, streaming is paused although further packets are incoming to the queueing buffer which are not useable any more. This is the current operation of PFC because data loss is not allowed in a data center for which the PFC protocols was originally designed.

Since the video packets are no longer usable, pause operation and preserving the video packets is no longer valid during this transition period. During this period, the packets for steaming shall be discarded and critical traffic shall continue to be sent. A more efficient operation method is to discard the unusable video packets until useful video packets are sent again when video adaptation to a lower quality matching the available bandwidth, or the link bandwidth is recovered naturally or by switching to a new link with sufficient bandwidth. If another ISS (or EISS) connection becomes available for the video stream application, data frame can then be forward dynamically at the bridge. (Table 15)

Table 15 Gaps between Current PFC (Std.802.1Q-2014) and Functions to be enhanced

Current PFC (Std.802.1Q-2014)	Functions to be enhanced
8(max) links can be independently paused and restarted by queue control. Only no loss is acceptable for data center environment.	Not only "pause" but also "discard" are acceptable depending on data attributes to express a variety of QoS requirements in factory applications.
There is no specific description about "frame distributor"	Dynamic frame distributor mechanism is required to follow rapid changing bandwidth and to avoid burst losses for each ISS/EISS connected to a wireless media. Also see later description in Wireless link aggregation.
—	It is required to have negotiation function with factory applications based on data attributes. Data rate reductions is requested if the factory application indicates reduction is "acceptable" in the data attributes.

The issue here is to adapt to rapid changes in wireless environments while ensuring a variety of QoS requirements across the end-to-end connection of the whole network. The rapid flow

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[1] Section 36.1.1 in Std. 802.1Q-2014 says "Operation of PFC is limited to a data center environment."

control at the bridge based on information of data attributes and flow control over the entire network shall work together by a coordinator as shown in Figure 2.

Competition of wireless systems in unlicensed bands

As for the factory IoT, wireless technologies which work in unlicensed bands are used in many cases because they have large cost advantage in network deployment. Normally, such unlicensed bands wireless technologies have MAC layer functionalities which enable coexistence with various wireless systems; CSMA/CA of Wi-Fi and frequency hopping of Bluetooth, for examples. These functionalities make network deployment simple, however, stable quality of service is difficult to keep with such simple schemes especially when many wireless systems share the same wireless resources. It is because each wireless system, which consists of multiple wireless stations and is managed by a base station, works independently based on own probabilistic approach without any coordination with the other wireless systems. In the factory IoT usage scenarios, many wireless systems work in a broad area which is not separated completely in terms of wireless resource, and such competition of wireless systems in unlicensed bands are unavoidable.

For mitigating the impact of the competition in unlicensed bands, it is necessary to coordinate wireless systems in factory as much as possible. To assign channel of each wireless system according to required bandwidth of applications is one of simple examples of the coordination. Both of distributed manner and centralized manner can be applied for the coordination, however, wireless systems need to be connected to the same wired network for exchanging control data. Wired network of the factory IoT needs to handle the control data for the wireless system coordination in addition to application data of each wireless systems. Figure 19 illustrates overview of centralized type of coordinated wireless systems.

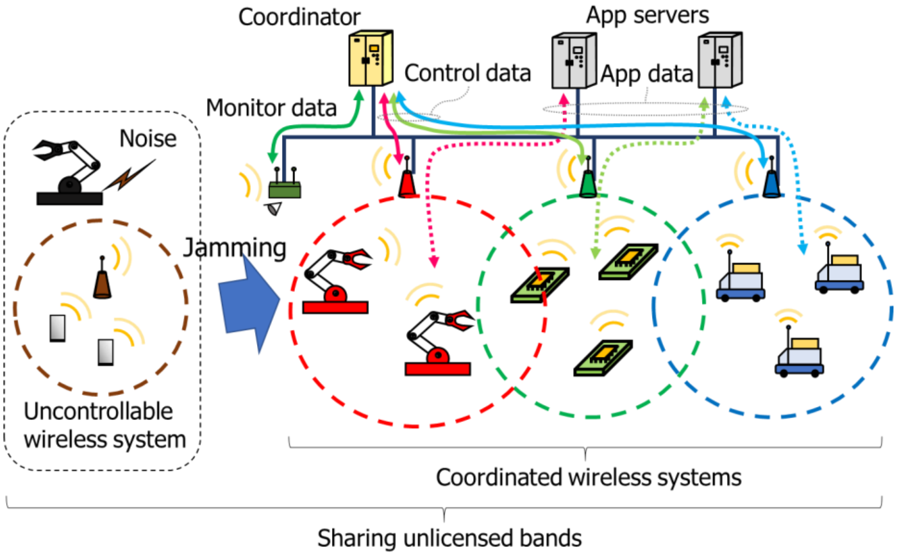


Figure 19 Overview of coordinated wireless systems

Ideally, all the wireless systems in an area should be connected to the same network and coordinated together. However, it is difficult to root out uncontrollable wireless systems in all the cases and noise from non-communication devices like machine tools also need to be taken into consideration. It is necessary to monitor wireless channels, analyze behavior of such interferers and estimate available wireless resources accurately for allocating wireless resources according to demands of applications. Wired network of the factory IoT needs to handle the monitoring data as well.

As latency of control data exchange and monitoring data exchange among wireless systems becomes lower, more efficient wireless system coordination becomes available. To improve latency of bridging is one of issues for the efficient coordination of the wireless systems.

Wireless link aggregation

As shown in Figure 4, wireless signal strength fluctuates largely and rapidly even in line-of-site environment inside factory. In such environment, it is difficult to keep stable bandwidth or low latency for factory IoT applications.

For improving stability of wireless link, taking advantage of diversity such as spatial and frequency diversities are effective. A simple way to take on gain of the diversity is to employ multiple wireless ports on each node or each wireless access point and use redundant wireless links for redundant data transmission.   Figure 20 illustrates examples of use of the multiple wireless ports. In Figure 20(a), a machine tool has two wireless ports and each wireless port has a wireless link with a different wireless access point. Potential bandwidth of each link fluctuates largely, and it becomes lower than bandwidth required by an application sometimes. However, correlation of the fluctuation is generally low if position and frequency of each wireless access point are different from those of another wireless access point. Therefore, such intermittent low bandwidth can be compensated if the wireless links are aggregated and data is transmitted redundantly through the aggregated links.

Figure 20(b)shows another example. In this case, a vehicle node moves inside a factory where large metal machines are located. Line-of-site relationship with a wireless access point is lost frequently as the vehicle moves behind the metal machine. In such a case, wireless systems generally attempt to do handover to the other wireless access point, however, it takes few seconds or more to complete the handover after the wireless link quality becomes bad. Applications are suffered from the bad wireless link for few seconds or more in this case. If the vehicle has multiple wireless links and use them as a redundant data path, impact of the bad wireless quality can be mitigated largely.

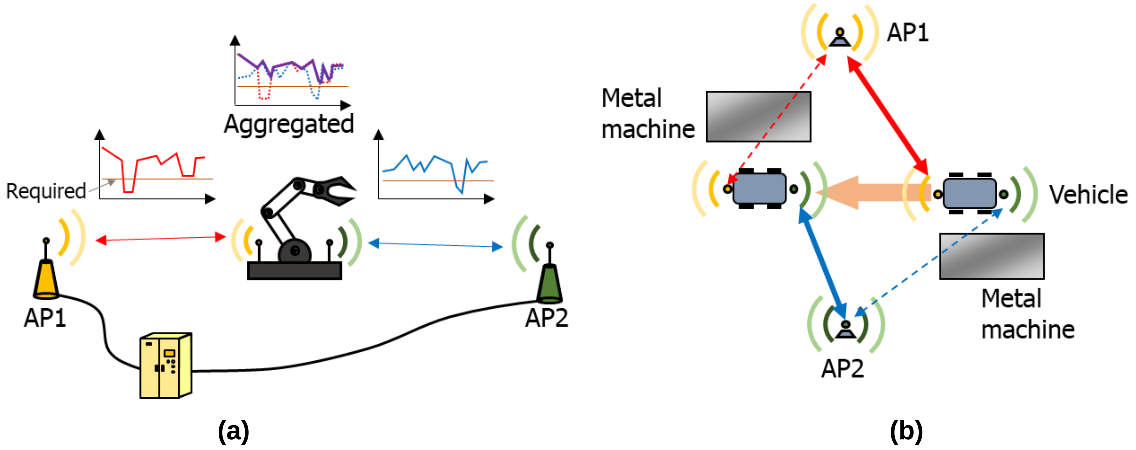
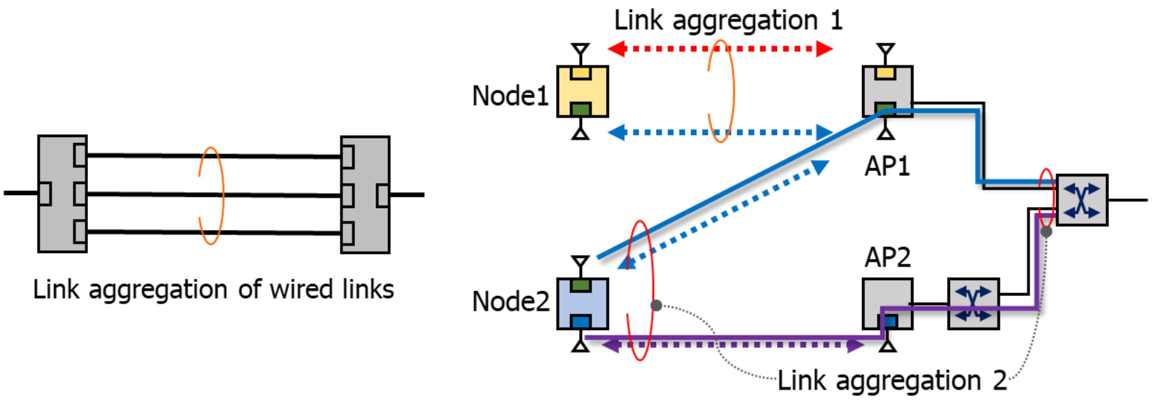


Figure 20 Examples of use of multiple wireless ports

Such redundant data transmission through aggregated paths can be implemented in various layers. However, bridging layer should be the most appropriate layer to handle paths aggregation for achieving the low latency performance required in the factory IoT usage. Link aggregation defined in 802.1AX is a related technology, however, it cannot be applied for the wireless link aggregation directly due to the following reasons:

- Main objective of link aggregation in 802.1AX is to increase bandwidth, and duplicated frame transmission is not allowed for maximizing total bandwidth of aggregated links. However, main objective of the wireless link aggregation for factory IoT use is to stabilize bandwidth and latency of data communication. Duplicated frame transmission through multiple wireless links needs to be allowed.
- 802.1AX mainly assumes wired links and single-hop link topology; Figure 21(a) shows an example for this. As shown as “Link aggregation 1” in Figure 21(b), if all the wireless ports are connected to the same wireless access point, the same aggregation protocol of 802.1AX may be applicable. However, a wireless node can have wireless links with multiple wireless access points in the wireless link aggregation usage. Link aggregation needs to be handled through multiple bridges shown as “Link aggregation 2” in Figure 21(b).



(a) (b)

Figure 21 Assumed link topology

Enhancements of IEEE 802 technologies for the future

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Conclusions

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Citations

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